S282 Astronomy

Multiwavelength views of the Andromeda Galaxy

Study time: 45 minutes

Summary

In this image-based activity you will study the Andromeda Galaxy (M31) and its small companion M32 through images obtained at X-ray, visible and infrared wavelengths. You will examine the images and interpret what you see with the aim of determining the main sources of emission at these wavelengths.

You should have read to the end of Chapter 2 of *An Introduction to Galaxies and Cosmology* before starting this activity.

Learning outcomes

- A recognition of the dominant sources of emission from a normal galaxy in these three wavebands.
- An appreciation of how different wavebands can be used to provide information on different constituents of a galaxy.

The activity

The activity uses images of the Andromeda Galaxy, M31, obtained in three different parts of the spectrum. M31 is the nearest large spiral galaxy to the Milky Way and is the most distant object visible to the naked eye (in reasonably good conditions).

The optical image, which is a negative image made using a photographic emulsion sensitive to blue light with wavelengths around 500 nm, is from the Palomar Observatory Sky Survey, carried out on the 48 inch Schmidt telescope at Palomar Observatory in California in the early 1950s. The infrared image was obtained by the Infrared Astronomy Satellite (IRAS) during its relatively short mission in 1983. This image is made in a band of wavelengths around 25 μm. The X-ray image was obtained by the German mission ROSAT (Röntgensatellit) in the early 1990s. These observations were made using a detector called the Position Sensitive Proportional Counter (PSPC) at the focal plane of an X-ray telescope.

Question 1

Why are the infrared and X-ray images obtained using satellites?

You will study each image in turn, identifying the main features and interpreting the sources of the emission at each wavelength. As well as the images, we have provided brightness contours for the infrared and X-ray images, which can be overlaid on the images to make comparisons easier.

- Start the S282 Multimedia guide, open the folder called 'Galaxies', then click on the icon for this activity (Multiwavelength views of the Andromeda Galaxy).
- Press Start to open the required set of images.

(Note that this image set is *not* available in the Image Archive.)

A window will open which displays optical image of the Andromeda Galaxy. On the right-hand side of the screen you will see a table of options that allow you to select different wavelength images and contour maps. (Note that in this image set – the term 'visible' has been used to denote optical observations at visual wavelengths. We shall refer these as the 'optical' images in these notes.)

- First, examine the optical image of M31, without any contours.

Question 2

Describe the appearance of the optical image and, using what you have learned about galaxies in Chapter 2 of *An Introduction to Galaxies and Cosmology*, identify and interpret the typical characteristics of a spiral galaxy.

The distance to M31 is about 690 kpc, so by measuring the angular extent of features in the optical image it is possible to determine their actual extent. In the next question you are asked to calculate the scale of the image and to then measure features using the on-screen ruler.

The on-screen ruler should be accessed in the following way:

- On the right-hand side of the screen there is a box that is labelled Launch Keyword Search and Measure Tool. Click on this.
- A list of all nine multiwavelength images will be displayed – for the image you wish to measure, click on the box labelled Measure image.
- The image to be measured will be displayed in a new window.
- To measure an angular extent in the image – position the cursor at one end of the feature you wish to measure. Press and hold down the left mouse button, then drag the cursor to the other end of the feature (you should see a white line extend between the two chosen points). The angular distance between the two points will be displayed.

Question 3

(a) Given that the distance to M31 is about 690 kpc, what is the scale of the image, i.e. how many pc in M31 correspond to 1 arcmin on the image? (*Hint*: see Equation 3.8 of *An Introduction to the Sun and Stars*.)

(b) Using the on-screen ruler, measure the diameter of the disc and the nuclear bulge in arcmin. Remember that the true shape of the disc is circular, we are seeing it at an angle, so you need to measure the major axes, which are not foreshortened. Estimate the size of the disc and bulge in kpc. How does this compare with the size of the Milky Way?

The apparent shape of the disc is an ellipse. If the disc is actually circular, then the angle of inclination θ to our line of sight can be found using the relation

$$\cos\theta = (\text{minor axis})/(\text{major axis})$$

The angle θ can be found using the $\cos^{-1}$ function which is defined in the following way.

If the cosine of an angle α has the value x, (i.e. $\cos\alpha = x$) then we can say that

$$\alpha = \cos^{-1}(x)$$

Note that '$\cos^{-1}(x)$' means 'the angle whose cosine has the value x'. It is important to realize that it *does not* mean $1/\cos(x)$.

You should be able to find the $\cos^{-1}$ function on your calculator – but note that it is sometimes called 'arccos'. (Remember that your calculator must be set up to work in degrees if you want the $\cos^{-1}$ function to give you an angle that is expressed in degrees.)

■ Use the $\cos^{-1}$ function on your calculator to find the angles (in degrees) that have the following cosines: 0.50, 0.866, 0.0, 1.0.

❑ $\cos^{-1}(0.50) = 60°$
$\cos^{-1}(0.866) = 30°$
$\cos^{-1}(0.0) = 90°$
$\cos^{-1}(1.0) = 0°$

So the angle of inclination θ can be found from

$$\theta = \cos^{-1}[(\text{minor axis})/(\text{major axis})] \qquad (1)$$

(A value of $\theta = 0°$ corresponds to viewing the disc face-on, whereas $\theta = 90°$ corresponds to viewing the disc edge-on.)

Question 4

Measure the major and minor axes of M31 and hence calculate the angle of inclination θ.

Now we are going to compare the appearance of M31. Examine, in turn, the infrared and X-ray images by clicking on the appropriate link in the navigation menu. (Note that the faint striped pattern running from the bottom left to top right in the infrared image is due to instrumentation effects.)

Question 5

Describe what you see in (a) the infrared image, and (b) the X-ray image including an estimate of the size of any interesting features. By looking back at what you have learned about stars, the ISM and the Milky Way, suggest what sort of sources might be causing the emission. Compare the images in all three wavelength bands and comment briefly on the similarities and differences. How does the amount of detail compare across the wavelengths? Which of the features you identified in Question 1 appear to show up in the infrared or X-ray?

As noted in the answer to Question 5, the resolution of the infrared image is much lower than that of the optical image – in fact about 60 times lower. The optical image was obtained with a resolution of about 2 arcsec – this means you should be able to distinguish two objects which are only 2 arcsec apart, whereas the resolution for the infrared image is about 2 arcmin.

Question 6

Using the results of Question 3, what are the distances between objects (i.e. within M31) that could be resolved at infrared and optical wavelengths? How do these distances compare to interstellar distances?

For observations using telescopes in general, i.e. including the infrared observations shown here, the angular resolution depends on the diameter of the main mirror (the larger the better) and the wavelength of the observed radiation (the shorter the better). Here, not only are the visual wavelengths shorter than the infrared ones, but the ground-based Palomar telescope is bigger than the space-based IRAS telescope. As a consequence of this, and other factors related to the design of the infrared detectors, the optical observations have a higher resolution than the infrared observations.

The X-ray images have a resolution of about 30 arcsec, and so are intermediate in resolution between the optical and infrared images. In the X-ray image, the close-packed sources in the galactic centre cannot be distinguished, so it's not easily possible to tell whether the emission there is diffuse or from point sources like the others.

Let's make the comparisons of the images a bit more rigorous. Start by overlaying each of the infrared and X-ray images with its own contours, so that you are clear in your mind about which contour 'islands' are peaks of brightness and which are actually 'dips', showing darker areas. For example the infrared image has elongated 'islands' around the bright ring, especially noticeable in the top left hand section, and a dark area in the disc within the ring but outside the nuclear bulge. Once you are comfortable with what the contours represent, go back and overlay each set of contours in turn on the optical image.

Question 7

With the optical image overlaid by the infrared contour, determine what the bright ring at 10 kpc in the infrared corresponds to in the optical. What do you think these features are, and why do they emit radiation in the infrared? Do you think the bright infrared emission in the nuclear bulge is due to the same sort of source?

Question 8

Now do the same sort of exercise with the X-ray contour overlay. What, if anything, do the X-ray sources correspond with at optical wavelengths? And what about comparing the infrared and X-ray images with each other? Do you find any common points?

Question 9

Finally, consider the dwarf elliptical companion galaxy, M32 (south of the nuclear bulge at RA 00h 42m 50s, Dec 40° 50′). Unlike the other companion galaxy, M110, this was well within the field of view for the IRAS and ROSAT surveys. At which wavelength(s) can you see emission from M32? What do you think it could be caused by? Why do you think it does not show up in all wavelengths?

Observing M31 for yourself

M31 is just about visible to the naked-eye – although it appears only as a faint ‘smudge’ and does require a dark observation site. You can locate M31 using your planisphere. At the beginning of July it is in the NNE at sunset, moving upwards and southwards until it is almost overhead at sunrise. Around midnight it is in the NE, with an altitude of about 20° (roughly the width of an outstretched hand at arm’s length).

Answers and comments

Question 1

The atmosphere absorbs strongly at infrared and X-ray wavelengths. From Figure 1.38 of *An Introduction to the Sun and Stars*, it can be seen that X-rays are completely blocked by the atmosphere. Although there are some ‘windows’ in the atmosphere at infrared wavelengths, at a wavelength of 25 μm the atmosphere is opaque. This means that X-ray and infrared observations (at wavelengths greater than about 10 μm) must be made from observatories in space.

Question 2

(Remember that this image is in the negative, so bright features look dark and vice versa.) This image shows a largish bright nuclear bulge set in a less bright disc. The outline of the disc appears to be elliptical, which implies that we are viewing it at quite a large angle of inclination. There is a clear bright spiral arm running up the left-hand side of the disc and around the top, and darkened lanes running down the right-hand side and around the bottom, where they are interlaced with bright arms. There are two bright dwarf elliptical companion galaxies, one appearing just below the nuclear bulge and the other towards the top right of the image. The rest of the small bright points around the image are foreground stars in the Milky Way.

The brightness of the bulge is due to the high density of stars that have a peak of their emission in the optical part of the spectrum. We can't really see any more structure in the bulge at this wavelength. The bright spiral arms are due not to the enhanced density, but to the luminous objects in the arms associated with star formation, such as HII regions, open clusters and OB associations (*An Introduction to Galaxies and Cosmology* Section 1.4.4). The rest of the disc is more dimly illuminated by stars. The darkened lanes are likely to be due to dust which obscures the visible light (*An Introduction to Galaxies and Cosmology* Section 1.2.3, compare also Figure 1.1).

Question 3

(a) The radius R of a distant object, in terms of half the angle α it subtends and its distance d is given by *An Introduction to the Sun and Stars* Equation 3.8

$$R = [(\alpha/2)/\text{radians}] \times d$$

Here, we want the distance D within M31 corresponding to 1 arcmin, which is therefore given by

$$D = [(1\ \text{arcmin})/\text{radians}] \times d$$

where $d = 690$ kpc.

Since 60 arcmin = 1 degree and 57.3 degrees = 1 radian,

1 arcmin = $1/(60 \times 57.3)$ radians = 1/3438 radians, so

$$D = (690/3438)\ \text{kpc} = 0.20\ \text{kpc}$$

So, 1.0 arcmin on the image is equivalent to 0.20 kpc.

(b) I obtained a value of around 120 arcmin for the diameter of the visible disc in the image, so the actual diameter is about 120 arcmin $\times$ 0.20 kpc arcmin^{-1} = 24 kpc. This gives a radius of 12 kpc, which is a little smaller than the visible disc of the Milky Way at 15 kpc. However, since the edge of the disc of M31 comes quite near the edge of the image, it is possible that the disc could have a greater extent than the image.

For the bulge, I obtained a diameter of 42 arcmin, which is equivalent to 42 arcmin $\times$ 0.20 kpc arcmin^{-1} = 8.4 kpc, this time a little bigger than that of the Milky Way at 6 kpc. (Remember that M31 is classified as Sb, whereas the Milky Way is SBbc, or similar, so we would expect M31 to have a relatively slightly bigger bulge.)

Question 4

In Question 3, the major axis of the disc of M31 was found to have an extent of about 120 arcmin. The minor axis of the disc image is about 30 arcmin across. The angle of inclination θ is given by Equation 1

$$\theta = \cos^{-1}[(\text{minor axis})/(\text{major axis})]$$

$$\theta = \cos^{-1}[(30\ \text{arcmin})/(120\ \text{arcmin})] = \cos^{-1}[0.25]$$

$$\theta = 76°$$

(*Comment*: given that the measurements of the major and minor axes are approximate, an appropriate way of quoting this result would be that the angle of inclination is between 70° and 80°.)

Question 5

(a) The most obvious features of the infrared image are a very bright region in the centre of the image, surrounded by much fainter emission, with a slightly branched bright elliptical ring at about 50 arcmin from the centre. The emission looks as though it extends beyond the top right and bottom left corners of the image, so the whole disc may well be bigger than the estimate we made in Question 3. There is also a small emission source towards the bottom left of the image. This doesn't correspond in position to either of the dwarf galaxies.

The image is much less detailed than the optical image, it is clearly at a much lower resolution – it is not possible to distinguish small features.

Infrared emission in astronomical sources typically arises from dust, which absorbs some of the visible and UV light from stars and HII regions and re-emits it at longer wavelengths. This dust occurs in the ISM and in circumstellar shells around old red giant stars.

(*Comment*: in order to emit so strongly at a wavelength of 25 μm, the dust must be heated to relatively high temperatures – above 200 K. This is hotter than most interstellar dust, which consists of relatively large grains at temperatures of below 100 K. However, very small dust grains or very large molecules can be heated to temperatures above 200 K after absorbing a single ultraviolet photon, and it is this material that gives rise to the emission seen at 25 μm.)

(b) The X-ray image is quite different to the optical and infrared images, in that there is very little sign of the disc. Like the infrared image, there is a bright source at the centre, but this time what we see around are a large number of smaller bright sources, with no real sign of any sort of diffuse emission over the whole galaxy. There may be some diffuse emission in the bright centre, but it is difficult to distinguish whether or not it is just due to the point sources running into each other.

By comparison with the X-ray map of Milky Way (*An Introduction to the Sun and Stars* Figure 9.16) the bright sources are likely to be interacting binaries containing neutron stars.

(*Comment*: of the 400 or so sources in the region of M31 identified during the ROSAT survey, 30–40% are thought to be either foreground or background sources, several were identified with known globular clusters in M31 and a few with supernova remnants. However the majority of the small sources in the image are thought to be interacting binaries, though in the bulge there may be some diffuse thermal emission from very hot gas. The emission from globular clusters arises from the interacting binaries that they contain.)

Question 6

2 arcmin in the image corresponds to about 0.4 kpc, or 400 pc. This is a much larger distance than that of nearly all the 100 brightest stars in Appendix A4 of *An Introduction to the Sun and Stars*. An angular resolution of 2 arcsec corresponds to (400/60) pc = 7 pc which is still further than any of the 100 nearest stars in Appendix A3 *of An Introduction to the Sun and Stars*, but a good enough resolution to distinguish far more detail – such as individual HII regions.

Question 7

With the infrared contours overlaid on the optical image, you can see that the infrared bright ring at 50 arcmin corresponds both to the star forming regions of the bright spiral arms and to the dark dust lanes you observed in the optical image. The bright regions correspond to HII regions where the new young stars are heating their surroundings. The dust lanes are likely to be obscuring similar HII regions. Much of the disc doesn't emit so strongly in the infrared and doesn't show clear dust lanes at visible wavelengths, so presumably contains either less dust, (or, as noted above in the answer to Question 5, dust with larger grains), or doesn't have such a strong heating mechanism. It's also clear that the very bright area in the centre does correspond to the centre of the bulge with its dense population of stars, so it seems likely that much of the bright emission from the centre of M31 is due to emission from circumstellar shells which exist around giant stars.

(*Comment*: the isolated source towards the bottom left corresponds to a foreground (Milky Way) star which is a red giant surrounded by circumstellar dust.)

Question 8

Overlaying the X-ray contours on the optical image confirms that not many of the X-ray sources correspond to anything at optical wavelengths. We would not expect to be able to see enough detail in this optical image to be able to distinguish binary stars, so would not expect to be able to spot a direct correspondence. Again the bright centre clearly corresponds to the centre of the bulge, as discussed above this may be partly due to very hot gas within the bulge.

The other obvious correlation is with the dwarf galaxy M32, see Question 7.

There is very little in common between the infrared and X-ray images apart from the bright galactic centre. Since the emissions arise from quite different sources this is to be expected.

Question 9

M32 shows up clearly at both optical and X-ray wavelengths, but not in the infrared. Being an elliptical galaxy it contains many stars, shining at optical wavelengths, but very little gas or dust, so there is no mechanism for emitting in the infrared. The X-ray emission arises, at least in part, from a number of interacting binary stars.

(*Comment*: it has been also suggested that M32 may contain a massive central black hole, which might give rise to some the X-ray emission from an accretion disc around it, but the evidence to support such a claim is not strong.)